Optical Thin Film Modeling

Using FTG's FilmStar Software

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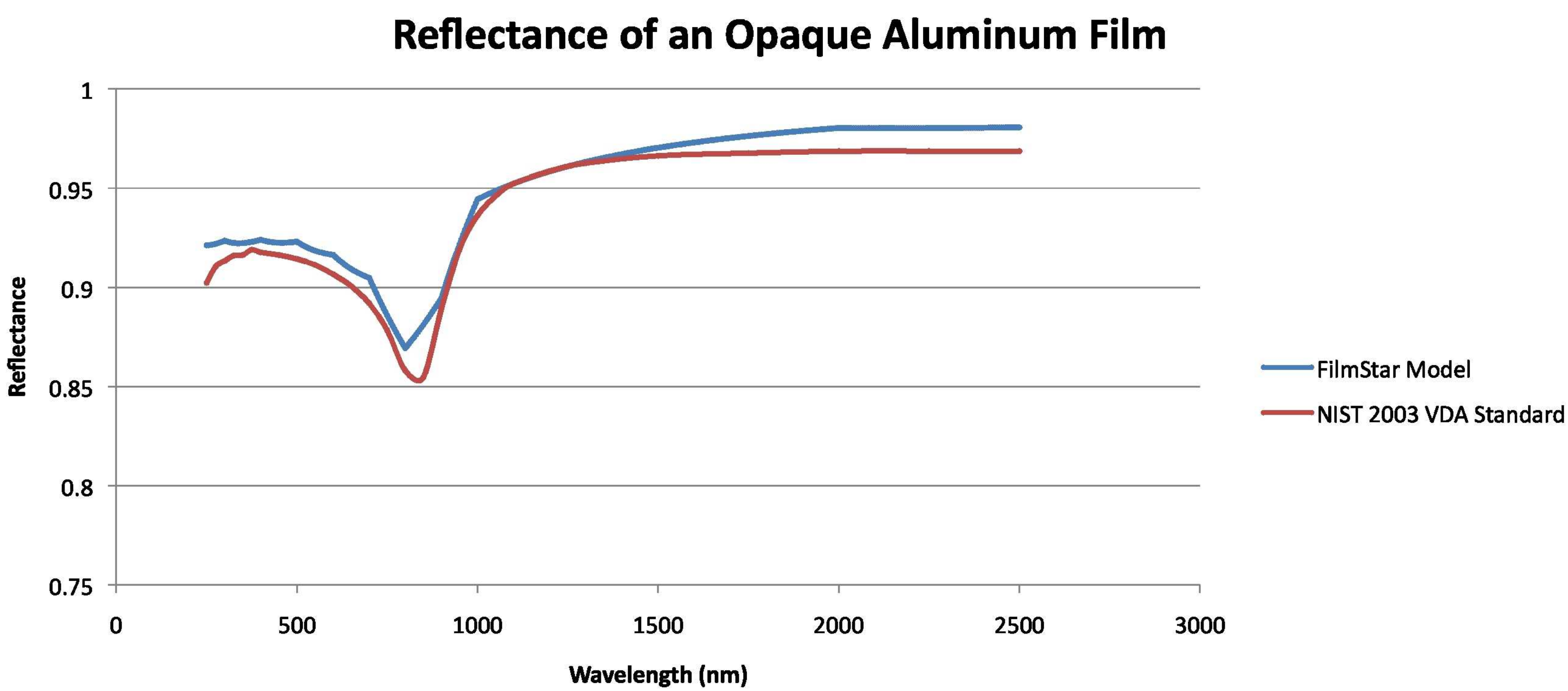
Optical Background

- Every material has basic optical properties that define its interaction with light
  - The index of refraction (*n*) and extinction coefficient (*k*) vary for the material as a function of the wavelength of the incident light.
- Also significant are the phase velocity and polarization of the incident light
- These inherent properties allow for the accurate modeling of light's behavior upon contact with a surface
  - Reflectance, Transmittance, Absorptance

Reflectance Curve of an Aluminum Mirror

- Comparison of modeled opaque Aluminum film (left) to NIST Standard for Vapor Deposited Aluminum (right)



Optical Background

- Reflectance is calculated by:
  $R = (N_{sub} - N_{med})^2/(N_{sub} -$
  - $N_{med} = 1$ for vacuum, ≈ 1
  - $N = n - ik$; complex whe
    negligible
- For glass (SiO_2), $n \approx 1.$
  0 in the visible range
  - R = .04, or 4% at each
    interface
- For a lens, ~8% of inci
  light is lost
  - Imagine with complex,
    multiple optic system!

Absorptance in glass is negligible for visible light

Unwanted Reflectance

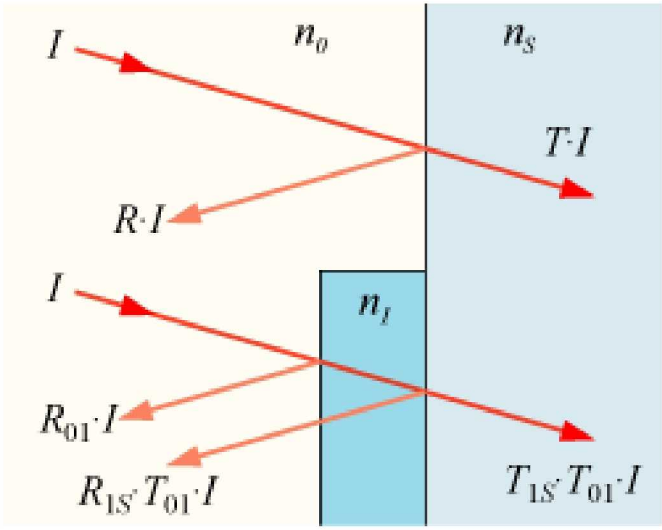
- By the time light reaches a sensor, consequential loss can occur.
- This has obvious negative effects on data gathering ability.
  - Less light received, less information to analyze
- Reflectance must be minimized in order to maximize throughput.
  - Or for mirrors, reflectance would ideally be maximized.
    - A similar technique is used.

Optimization of Optical Behavior

- Thin films of materials with different optical properties can enhance the desired effects of a surface.
  - For a single layer anti-reflective coating:
    - $n_{medium} / n_{coating} = n_{coating} / n_{substrate}$
    - $n_{coating}$ = [redacted], since $n_{medium} = 1$ for vacuum/air
  - Can be further optimized by adjusting layer thickness.
    - Even more so by introducing multiple layers.

Optimization of Optical Behavior

- Since glass has an index of refraction of *n = 1.52*, the ideal single layer AR coating has *n = 1.23*
  - Closest common film is MgF_2, *n = 1.38*
    - Can reduce loss to ~1%, a 4x improvement over bare surface.

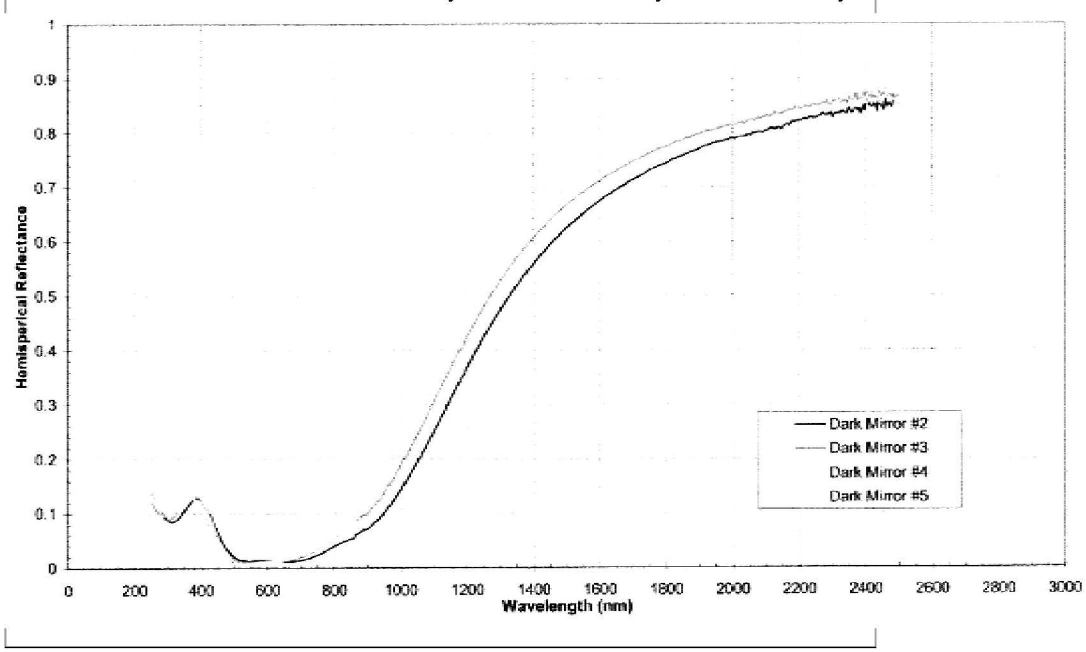


Optimization of Optical Behavior

- Reflectance is actually optimized for a defined wavelength range
  - Since *n, k* are wavelength specific
- Principle is used to create coatings with a specific purpose
  - Most instruments focus on a specific wavelength range as well
  - e.g. – GSFC Dark Mirror Coating
    - Minimizes reflectance in the visible spectrum

Optimization of Optical Behavior

- Comparison of measured dark mirror (left) reflectance to modeled (right)
  - Standard layer thicknesses were obtained from George Harris of SGT, Inc./GSFC Code 546
    - From substrate: 100nm Al, 37-40 nm SiO, 5-7 nm Cr, 50-53 nm SiO
  - Thicknesses used in model:
    - From substrate: 100nm Al, 38nm SiO, 12nm Cr, 50nm SiO

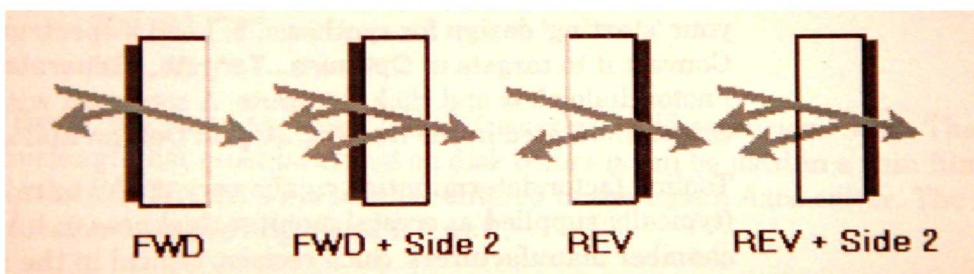


Use of FilmStar Software

- FilmStar automates the calculation of reflectance (as well as transmittance, absorptance) for each wavelength
  - Uses data tables of *n* and *k* values for materials
    - Many common materials included, but still a need for others along with extended/updated tables of existing materials
- Task broken into two individual pieces of software
  - Index and Design
    - Index: creates/modifies data tables of n, k values
    - Design: the workhorse
      - Incorporates data tables, calculates behavior, and allows for modification and optimization.

Use of FilmStar: Design

- Allows for creation of custom coatings
  - First, a substrate is selected from materials
  - Can model bare substrate, one layer, or numerous layers
    - Each layer also to be selected from list of materials
    - Each set to custom thickness
- Automated calculation of optical behavior
  - Numerous options for results
    - %R, %T, %A, thickness relationship
  - Makes calculation using *n, k* values
    - Leaves option for what reflections to take into account



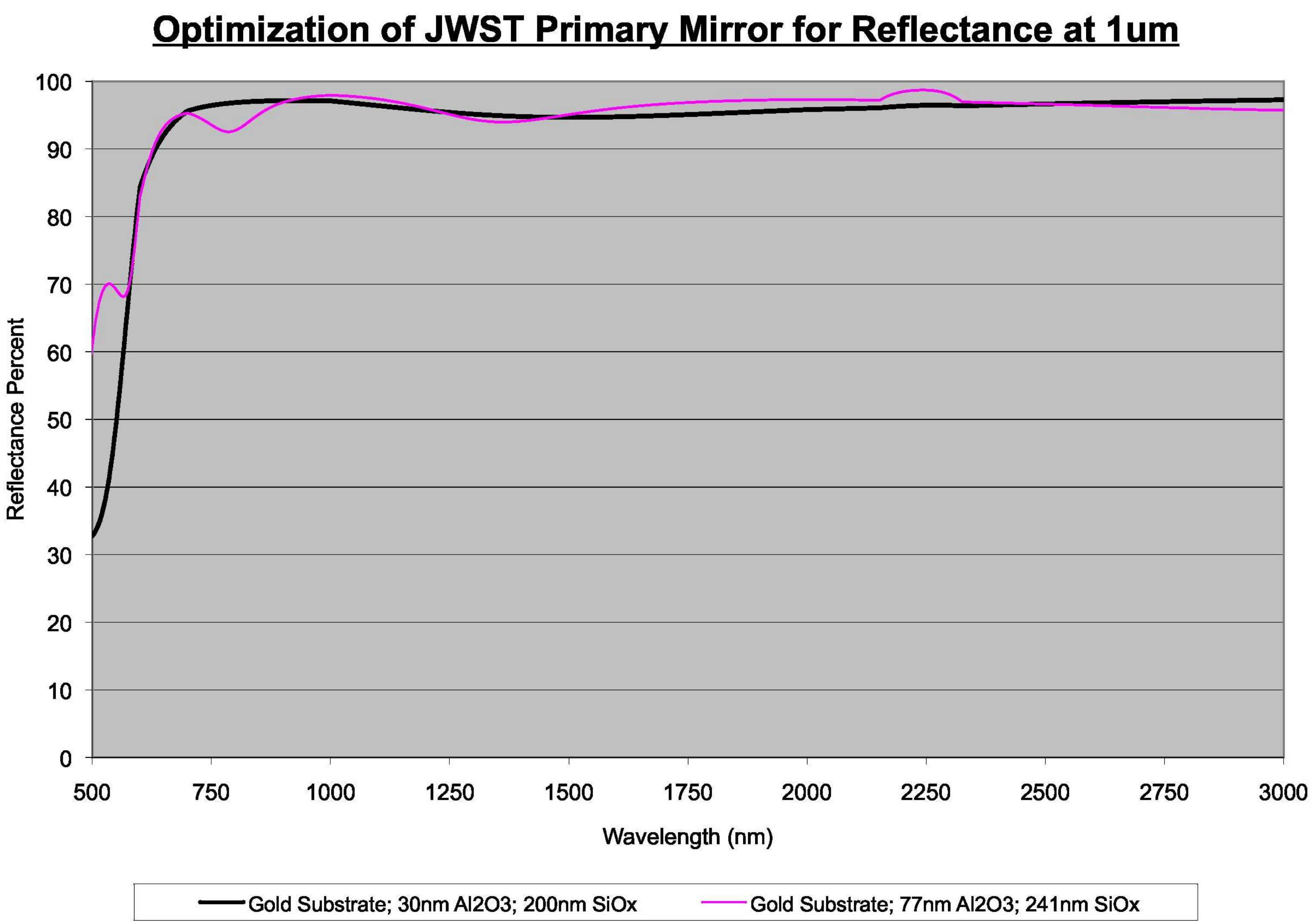
Use of FilmStar: Design

- Layer thickness is first input manually
- Design then has a function for optimization
  - User selects a target reflectance (or A, T)
    - Can be selected for any wavelength range
  - User also has option to select what layers the program is allowed to adjust
  - When inputs are set, the program calculates the coating thickness required to meet target
    - Further inputs for maximum change, and number of iterations to perform

Optimization of a Thin Film

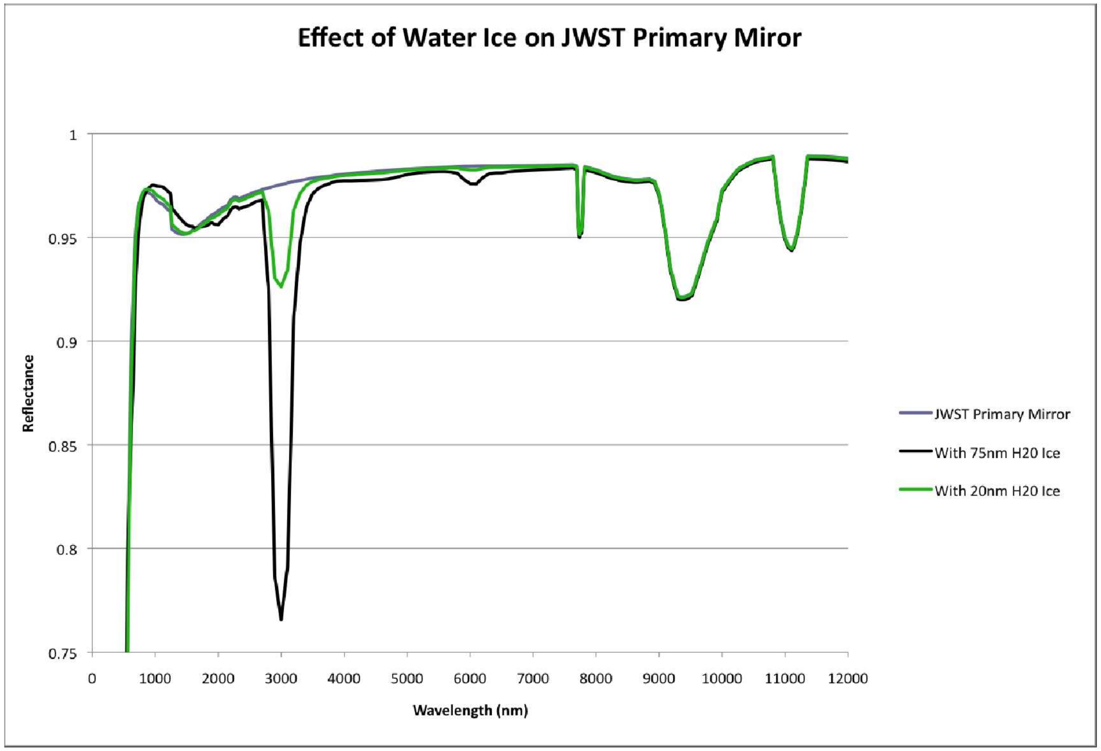
- The JWST Primary Mirror has a base gold film, with a protective coating
  - Gold is thick enough to be considered substrate
- Optimizing the surface coating
  - Exact "formula" unknown, but similar concept used
  - Started with formula of:
    - Gold Substrate; 30nm Al_2O_3; 200nm SiO_x
  - Optimization for 1µm led to formula of
    - Gold Substrate; 77nm Al_2O_3; 241nm SiO_x
  - Increase from 97.1 %R to 97.9 %R at 1µm

Optimization of a Thin Film



Contamination Modeling

- Extra advantage to thin film modeling
  - Can also model films that *shouldn't* be present
    - Determine worst case scenarios for materials expected to be present.
      - Need to assume a perfect thin film
    - e.g. – Water ice on JWST Primary mirror



Contamination Modeling

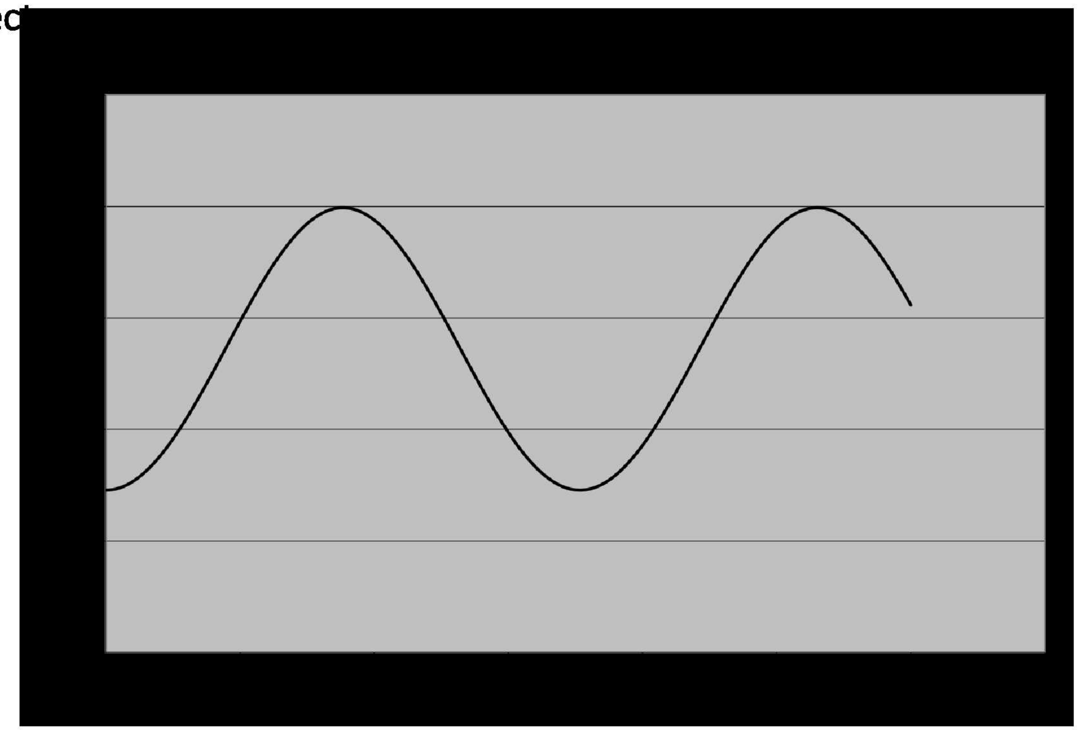
- Further capability of determining contamination details from observed data
  - Change in behavior of sensors can be related to a contamination film on it or in optics path
- Possible to classify the type of contamination, as well as thickness
  - Also possible to rule out a specific contaminant, or contamination in general

Contamination Modeling

- SDO HMI Throughput Issue
  - Data showed an apparent dramatic signal difference between two CCDs at -90C in thermal vacuum cycling.
    - Possibly a significant change in throughput, or possibly data error
    - Film of water ice proposed by vendor, among other possible issues.
  - Exact CCD layering was unknown, but similar was modeled.
    - Created analysis of transmittance vs. thickness of water ice on a likely CCD substrate
      - At 473 nm, the peak wavelength of LED test source

Contamination Modeling

- Model showed a maximum increase of ~3% in transmittance with water ice on SiO_2 substrate (a likely CCD surface)
  - Significantly less change than what was observed.
  - Meant that water ice contamination was probably not the culprit
    - Limited data made it difficult to determine what was or was not the real cause
    - Also possible the effect was a data error in CCD efficiencies, not a real transmission effec



Limitations and Weakness

For Thin Film Modeling

- Need a complete and accurate model of the optical system
  - Inaccuracy in layers, materials, or thickness can greatly affect the outcome
  - Must interact with instrument teams to increase modeling strength
- Limited n, k data for some materials
  - Possibility for in house measuring

Limitations and Weakness

For Contamination Modeling

- Must assume a perfect thin film
  - Contamination is often scattered and/or localized
    - Water condenses in spots converging outward
      - Think of frost on a car windshield
  - Possible interpretation as a weighted average of contamination's effect on the exposed optical area
- Must have an idea of what contaminants to expect
  - Some cases fairly predictable
    - Based on surface temperature for condensation

Future Capabilities

- Possibility for determining *n,* k values for less common materials, especially contaminants
  - Can be performed with existing spectroreflectometer instruments and extended FilmStar software: *Measure*
- Increased interaction with optical systems designers will vastly improve the modeling capability
  - Should also lead to better understanding of contamination limits, and improved contamination control plans